Transportation Research Part B 48 (2013) 17–30

Contents lists available at SciVerse ScienceDirect

Transportation Research Part B

journal homepage: www.elsevier.com/locate/trb

Integrated modeling framework for leasing urban roads: A case study of Fresno, California

Omid M. Rouhani [a,*], Debbie Niemeier [a], Christopher R. Knittel [b], Kaveh Madani [c]

[a] Department of Civil and Environmental Engineering, One Shields Avenue, University of California, Davis, United States
[b] Sloan School of Management, Massachusetts Institute of Technology, 100 Main Street, E62-513, Cambridge, MA, United States
[c] Department of Civil, Environmental, and Construction Engineering, University of Central Florida, Orlando, FL, United States

ARTICLE INFO

Article history:
Received 5 June 2012
Received in revised form 10 October 2012
Accepted 10 October 2012

Keywords:
Urban road networks
Privatization
Ownership structure
Public–private partnership
Fresno
California

ABSTRACT

Increasing private sector involvement in transportation services has significant implications for the management of road networks. This paper examines a concession model's effects on a road network in the mid-sized city of Fresno, California. Using the existing transportation planning models of Fresno, we examine the effects of privatization on a number of typical system performance measures including total travel time and vehicle miles traveled (VMT), the possibility of including arterials, and the differences between social cost prices and profit maximizing prices. Some interesting insights emerge from our analysis: (1) roads cannot be considered as isolated elements in a concession model for a road network; (2) roads can function as complements at some levels of demand and become substitutes at other levels; (3) policy makers/officials should consider privatizing/pricing arterials along with privatizing highways; (4) temporally flexible but limited price schedule regulations should be part of leasing agreements; and (5) non-restricted pricing may actually worsen system performance, while limited pricing can raise enormous profits as well as improve system performance.

1. Introduction

The first major public–private partnerships (PPPs or P3s) in the U.S. transport sector began in 1989 with the construction of the E-470 Tollway, east of Denver, Colorado. Since then, the private sector has made many investments in both existing and new highways through P3s (Reinhardt, 2011). Advocates of P3s have claimed that a significant amount of private investment funding, ranging from $100 billion to $400 billion, is available to meet transportation needs in the U.S. This trend of increasing private sector involvement in transportation services has important, especially financial, implications for public road networks. Not only is this trend important for financing, but increased private sector involvement also has implications for quality of service, mitigation of environmental impacts, and addressing social issues (Chung et al., 2010; de Jong et al., 2010; Rouhani, 2009).

Given the social and economic costs caused by congestion and unmet demand (Winkelman et al., 2010), properly developed P3 business models may play an important role in better understanding and addressing the challenges faced by urban transportation systems. Currently, P3 contracts include a wide range of models: BOT (Build-Operate-Transfer), BOO (Build-Own-Operate), DBFMO (Design-Build-Finance-Maintain-Operate), concession, etc. (Arup and PB, 2010; Zhang,

* Corresponding author. Tel.: +1 530 204 8576.
E-mail addresses: omrouhani@ucdavis.edu (O.M. Rouhani), dniemeier@ucdavis.edu (D. Niemeier), knittel@mit.edu (C.R. Knittel), kmadani@ucf.edu (K. Madani).

0191-2615/$ - see front matter
http://dx.doi.org/10.1016/j.trb.2012.10.005

2005). In concession models, a subcategory of Brownfield projects[1] (Evenhuis and Vickerman, 2010; Reason, 2009), the private developer (a private consortium) is usually granted the right to collect tolls[2] from an existing facility under a long-term contract while public sponsors retain some control levers such as limiting toll levels (or toll ceilings) (Rall et al., 2010).

In the U.S., four prominent transportation assets have been privatized using the Brownfield model: the Indiana Toll Road, the Chicago Skyway, the Pocahontas Parkway (Virginia), and the Northwest Parkway (Colorado) (Reinhardt, 2011). The first long term concession of an existing toll road in the USA was the Chicago Skyway lease for 99 years in 2004, which costs $1.83 billion (Ortiz et al., 2008). The Indiana East West Toll Road (157 miles) was leased for 75 years with a $3.85 billion concession fee in 2006 (Crowe Chizek, 2006; Indiana Toll Road, 2012). The Indiana Toll Road contract set an example by showing that significant profits can be gained from road infrastructure. A thorough review of concession models used for roads is provided by Bel and Foote (2009).

A considerable amount of work has been done on reviewing real-life P3 projects (Bonnafous, 2010: Chung et al., 2010; Engel et al., 2003, 2006; Evenhuis and Vickerman, 2010), including the examination of a BOT project using various optimal road pricing models to assess the effects of regulations (Chen and Subprasom, 2007). However, few studies have developed theoretical models to analyze the principal impacts of such projects on actual road networks.

There have been studies that used extensions of common models, usually on smaller networks. For example, de Palma and Lindsey (2002) and de Palma et al. (2007) used a two-competing-road framework to examine the possibility of time-based congestion pricing, and to analyze maintenance and tolling decisions. Verhoef et al. (1996) and de Palma and Lindsey (2000) explored the dynamics between public and private roads. Winston and Yan (2011) used duopoly and monopoly structures to assess social welfare effects of highway privatization on two routes. Applying multi-class user equilibrium, Yang et al. (2002) investigated the effects that distributions of value of time have on traffic flow and profits of private toll roads for a small network. Rouhani and Niemeier (2011) examined the effects of different privatization structures on a small hypothetical network with two modes of transportation.

Other studies have taken a more general and practical network approach with the use of some simplifications. Zhang and Levinson (2006) applied an agent-based simulation model to a grid network to study the problem of road pricing on a highway network composed of independent profit-maximizing links with a repeated road pricing game between autonomous links. This study relies on a key assumption: that the Nash equilibrium is not unique or even does not exist because link owners do not have complete information. That is, the authors assume that links try to achieve profit maximization by adjusting their prices iteratively to reach a toll value that can neither be raised nor lowered without losing profits. Each link owner fits a quadratic curve in the profit–price domain. Although this approach is very effective in terms of computation time, the way in which demand (profit)–price relationship is estimated has major limitations. First, the assumption that profit–price relationship is quadratic should be tested (hypothesized) and then applied. It is possible that different functional forms perform better in different settings. Second, the study simply assumes that link owners cannot have enough information on the effects of other links' prices, and as a result, they reach a solution which is not a Bertrand–Nash equilibrium. Third, the final solution is not necessarily at equilibrium and may result in a situation, where one or more link owners applied higher tolls than their Bertrand–Nash equilibrium tolls and other links/owners charge lower tolls than their Nash equilibrium tolls, based on their response functions. Fourth, this procedure can be applied only to autonomous links and cannot model more complex settings in which each firm/private entity owns more than one link. And finally, no information can be gained about demand functions and their attributes, cross price effects, elasticities, etc. Here, we have employed an alternative approach that addresses each of these issues.

In another study, Zhang and Levinson (2009) simulated the evolution of a grid road network and evaluated the short-run and long-run network performances under various ownership structures (private/public and centralized/decentralized). The study assumes a competitive market, which may not be realistic because of spatial restrictions and possible barriers to entering the road network market.

Few studies have analyzed real network implications. Zhang (2008) developed a model that considers the combination of pricing, investment, and ownership to study welfare impacts of road privatization on a real-size network (Twin Cities network) using an evolutionary simulation model. Dimitriou et al. (2009) developed a game-theoretic formulation for the joint optimization of capacity investments and toll charges within general road networks, examining some real-life issues such as regulations on tolls for private highways.

Finally, a key gap in the literature also exists for studies that have specifically modeled some of the policy implications of urban road network privatization, especially in case of concessions. Study and modeling gaps exist in the following areas: the inclusion of secondary roads like arterials, the differentiation between profit maximizing and social cost pricing, the peak vs. off-peak analysis, and the clear distinction between monopolistic and oligopolistic power of road owners. To help fill the gap in knowledge, we employ a distinct integrated modeling framework to analyze the effects of applying a concession model to a real city network. The model integrates of the following modules: demand analysis, interactive profit maximization using

[1] PPPs consist of two broad categories, in terms of mission: "Greenfield" projects that develop new infrastructure and "Brownfield" projects that operate, maintain, and preserve or improve existing infrastructure and usually are accompanied by tolling.

[2] The exceptions are shadow tolls and availability payments. For shadow toll roads, as in the case of the UK (NAO, 1998), highways agencies pay the private operator(s) a fee based on the vehicle kilometers driven on the roads. Availability payments are a means of compensating a private concessionaire for its taking on responsibility to design/construct/operate a roadway and made by a public source (AASHTO, 2012).

game theory concepts, and modified traffic assignment. Applying minor modifications due to using practical data, the model is an application of our previous theoretical study (Rouhani and Niemeier, 2011) to a real case.

This paper investigates the effects of the concession model on a road network of an urbanized city: Fresno, California. We use the existing transportation planning model and our integrated modeling framework to examine the following concepts: the level of competition between private owners, the effect of privatization on system performance measures such as total travel time and vehicle miles traveled (VMT), the possibility of involving arterials in the process, the difference between social cost prices and profit maximizing prices and their associated revenues, the complementarity versus substitutability relationship among roads, demand functions' estimation using different functional forms, and the welfare analysis of various ownership structures and scenarios.

2. Model framework

We apply the bi-level programming concept (Yin, 2000) to structure the problem. At the upper level, city or state officials (planners) must decide which roads are to be leased or privately constructed and what kinds of regulations are required (e.g., price ceilings). The common theoretical goal of policy makers is maximizing the sum of consumers and producers' welfare surplus. The policy maker's objective function can be calculated based on total travel time, total gas consumption and emissions, total profits gathered, or a combination of any of these in monetary terms. Here, we used total travel time as the policy maker's objective function. Since one of our goals is to find a good solution for the policy maker problem, we construct and analyze various scenarios using different combinations of private streets with varying sets of regulations. An alternative method, which could be applied, is to use an optimization algorithm, such as a Meta-Heuristic algorithm (Poorzahedy and Rouhani, 2007) to find the optimal solution for the policy maker problem (first level). In the second level, new street owners (or street leasers) decide how much to charge users to maximize their profits. At the lowest level (third level), users of the network would choose the streets (paths) or modes to reach their destinations. The bi-level model considers the second and third levels.

2.1. Mathematical model-Road owners' model

Road owners attempt to maximize their profit (π_k) which is the sum of the toll revenues gathered from the segments or the links of their road $\sum(\tau_{ij} \cdot x^*_{ij}(\tau)$ for all the roads owned by firm k which comprise the F_k set, $(i,j) \in F_k$), minus the costs of collecting the tolls for the firm ($C_{F_k}(x_{ij})$). Note that the demand for the link $i-j$ ($x^*_{ij}(\tau)$) is a function of a vector of tolls, not only the firm's own tolls (we will examine this relationship later). Each firm only controls the tolls on its own links and has no control over the tolls charged by other firms. So, the tolls determined by other firms are exogenous, i.e., Firms have an oligopolistic power due to spatial restriction and limited available capacity, and can change their charged tolls based on other firms' responses. So, the prices are not perfectly competitive and constant. Also, note that tolls are usually capped by public officials ($\bar{\tau}$, like the case for toll ceilings). This problem can be formulated as follows:

$$(Maxprofit)\ \underset{\tau_{ij}}{Max}\ \pi_k = \sum_{(i,j)\in F_k} \left(\tau_{ij} \cdot x^*_{ij}(\tau) - C_{F_k}(x_{ij})\right) \tag{1}$$

$$s.t.: \quad \tau_{ij} \leqslant \bar{\tau} \tag{2}$$

where x^* is the user equilibrium (UE) flow with fixed demand (or variable demand) in the network that is the solution of the following mathematical problem:

$$(\text{UE}) \quad \underset{x}{Min} \quad \sum_{(i,j)} \int_0^{x_{ij}} C_{ij}(u)du \tag{3}$$

$$s.t.: \quad \sum_{p\in P_{ks}} x_p^{ks} = d^{ks},\ \forall (k,s) \in P \tag{4}$$

$$x_p^{ks} \geqslant 0,\ \forall p \in P_{ks},\ \forall (k,s) \in P \tag{5}$$

$$x_{ij} = \sum_{(k,s)\in P} \sum_{p\in P_{ks}} x_p^{ks} \cdot \delta^{ks}_{ij,p},\ \forall (i,j) \in A \tag{6}$$

where x_{ij} is the flow in link (i,j) and x_p^{ks} is the flow in path p ($p \in P_{ks}$) from origin k to destination s, $\delta^{ks}_{ij,p}$ is 1 if link $(i,j) \in P_{ks}$, and 0 otherwise. The flows are generated by the travel demand from k to s, d^{ks}, which can be non-constant, but still exogenously determined (Sheffi, 1984).

This model also uses the Wardrop's principle (Wardrop, 1952) as its principle, with C_{ij} as the generalized cost associated with traveling on link $i-j$ rather than just the travel time t_{ij} (replacing t_{ij} with C_{ij} in the UE problem):

$$C_{ij} = t_{ij}(x_{ij}) + \beta_{ij} \cdot \tau_{ij} \tag{7}$$

where τ_{ij} is the charge for using link $i-j$, determined by the link owner from the higher level model (Nagurney, 2000) and β_{ij} is the value of time coefficient which transforms the charges in dollars (or cents) to costs in terms of time. Since the value of time varies for different users, we need multi-user equilibrium to address the difference in behavior.

The above-mentioned mathematical model only considers the profit maximization problem of firms. The policy maker level could be also added to the problem formulation. In that case, a policy maker can implement some control variables such as the toll ceilings, the level of competition between firms (monopoly vs. oligopoly), and the set of roads (links) to be privatized. By adding the policy maker level, we could solve for the optimized levels of control variables. However, instead of making the model more complex and adding another level, we will examine a limited number of ownership structures separately in the social welfare analysis section (Section 4.3).

2.2. Profit maximization, game theory, and response functions

The mathematical model presented in Section 2.1 is a bi-level model that is difficult to solve, particularly for large and realistic networks. However, this model can be simplified to some extent. In practice, owners try to estimate their links' demand functions. Practically, they are interested in the own toll prices and the cross prices. Thus, the problem can be solved for various sets of prices (tolls) in order to find the demand functions for each road, based on its own prices and other roads' (or cross) prices. Private owners do not possess perfect knowledge about other road owners' pricing decisions, which causes uncertainty about the demand functions. Nonetheless, because of the dynamic nature of the problem involving trial and error, it is assumed that road owners can collect sufficient information to establish the demand functions.

Using the existing transportation planning models, the lower level model (UE) can be run for different sets of random prices to find the resulting travel demand for each road. Note that the model is not required to be run, using a large number of price sets for three reasons: (1) in real-life, private owners can only collect data for small price sets; (2) prices are only effective in discrete levels (e.g., from the users' point of view, 20 cents/mile is not much different than 21 cents/mile); and (3) adding data will not improve the regression results if the sample is large enough. So, the mathematical formulation of the model can be revised as follows:

$$(Maxprofit)\ \underset{\tau_{ij}}{Max}\ \pi_k = \sum_{(i,j)\in F_k}\left(\tau_{ij}\cdot x^*_{ij}(\tau) - C_{F_k}(x_{ij})\right) \tag{8}$$

$$s.t.:\quad \tau_{ij} \leqslant \bar{\tau} \tag{9}$$

The difference between this model and the previous model (Eqs. (1)–(6)) lies on realization of the demand function, x_{ij}. Knowing the demand functions, private owners can solve the maximization problem. However, they can only determine the prices charged on their own road, and the prices of other roads are exogenous if there exists a private road owned by other firms. In a static framework, we can develop road owners' decision making model using profit maximization and non-cooperative game theory concepts. If there is no other competitor (the monopoly case) solving the maximization problem is straightforward. Assuming the unconstrained optimization for simplicity, the first order conditions for different links to find the prices that maximize the profits (satisfy the system of equations) are as follows:

$$\frac{\partial \pi_k}{\partial \tau_{ij}} = 0 \text{ or } \sum_{(i,j)\in F_k} x_{ij}(\tau) + \sum_{(i,j)\in F_k}\left(\frac{\partial x_{ij}(\tau)}{\partial \tau_{ij}}\cdot \tau_{ij} - \frac{\partial C_{F_k}(x_{ij})}{\partial \tau_{ij}}\right) = 0 \quad \forall (i,j)\in F_k. \tag{10}$$

When more than one firm exists, road owners may compete or cooperate with each other to maximize their profits, knowing their own streets' demand function and the possible choices of other owners. We assume the Bertrand–Nash equilibrium concept (Magnan de Bornier, 1992) in which each player (road owner) anticipates the equilibrium prices of the other players, and no player has anything to gain by changing his or her own strategy unilaterally (Bierman and Fernandez, 1998). The first order condition will be the same as before. However, all the links are not owned by one firm. So, each firm sets up its own response function (pricing in response to other firms' prices) as follows:

$$\text{F.O.} \rightarrow \tau_{ij}(\bar{\tau})\ \forall (i,j)\in F_k \tag{11}$$

where $\bar{\tau}$ is the vector of tolls (prices) charged by other firms. We can solve the system of equations involving all response functions and find the best mutual prices. Bertrand–Nash equilibrium assumes that non-cooperative games are prevailing (Mallozzi, 2007; Madani and Dinar, 2012). In other words, firms do not collude, based on the Bertrand–Nash equilibrium. In reality, collusion may happen and if so, a cooperative game framework should be used (Watson, 2002; Madani, 2011).

To consider cooperative games, there should be some conjectural variation ($\frac{\partial \tau_{lm}}{\partial \tau_{ij}} \neq 0$ where links $l-m$ and $i-j$ are not owned by the same firms). But, we will observe later that in our case study, the oligopoly and monopoly result in close prices. So, the collusive assumption would not change the results dramatically, assuming that the collusive solution is between the monopoly and non-cooperative oligopoly cases. For further information about conjectural variation concept, see Jacquemin (1987) or Waterson (1984).

3. Case study – Fresno, California

The city of Fresno is located in the Central Valley of California. As of 2011, the city's population was 480,000, making Fresno the fifth largest city in California, and the largest inland city in California (City of Fresno, 2012). The city maintains a standard four-step transportation planning model that is calibrated for the year 2030. The network consists of 20,865 links and

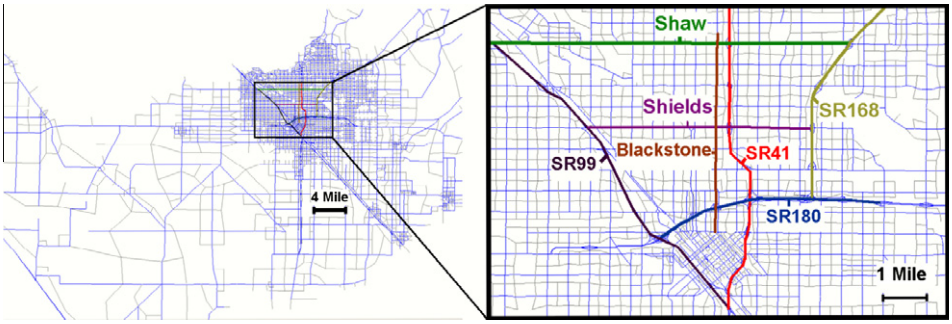

Fig. 1. The Road network of the city of Fresno, California. *Source*: Transportation planning model, city of Fresno.

Table 1
Main characteristics of the candidate roads. *Source*: Transportation planning model, city of Fresno – 2030 forecasts.

	Name	Length-private (mile)	Freeflow speed (MPH)	AM peak VMT (base-hourly)	Offpeak VMT (base-hourly)
HW1	SR168	4.92	65	70,265	28,009
HW2	SR41	7.51	65	133,070	56,900
HW3	SR180	5.23	58	68,701	30,138
HW4	SR99	8.56	65	136,263	55,509
Arterial1	Shaw	8.47	40	44,163	14,710
Arterial2	Shields	5.32	40	19,943	7147
Arterial3	Blackstone	4.73	40	21,044	5420

1852 traffic zones (Fig. 1). We selected seven segments of roads transecting the urban area as candidates for privatization on the basis of both profit making and reducing congestion. The candidate roadway segments are on four highways: SR168, SR41, SR180, and SR99; and on three arterials: Shaw, Shields, and Blackstone. Table 1 reports the main characteristics of the candidate roads.

The applied transportation planning model is a static deterministic single user equilibrium model (Sheffi, 1984). We believe that it is reasonable to assume static conditions given that our interest is not in real-time prices for the private owner. Admittedly, a stochastic model could be more realistic. But, the common existing planning models and the model used as our case study do not include this characteristic. In addition, using single user equilibrium is undeniably inappropriate, especially because value of time, which varies for different classes of users, has major impact on the analysis. However, city-size models usually do not cover multi-class user equilibrium models.

The model only estimates short-run results. In the long run, both public and private entities can affect the results by adding capacity. In addition, Bertrand–Nash equilibrium is theoretically a static model that replicates a dynamic game.

Other specific simplifying assumptions of the study are as follows:

– The costs of installing tolling facilities are assumed to be negligible or independent from flows/tolls (zero costs), i.e., the first order conditions do not include a term for the costs.
– In addition to its own prices, each link's travel demand is a function of other links' prices. This is examined in the next section.
– Road owners apply a constant mileage-based toll rate on the whole road (consisting of various segments), although in practice, variable pricing can be the optimal policy for profit maximization (Wang et al., 2011).
– An average user values time at $14/h. Using the load factor of 1.4 persons/vehicle, the value of time for each vehicle is about $20/h ($14 \times 1.4$). So, β_{ij} (from Eq. (7)) equals 3 min per dollar (a $1 charge on a link is valued at 3 min (60 min per hour/$20 per hour)).

4. Results

4.1. Demand analysis

As discussed, here the basic assumption is that each road's travel demand is a function of other roads' prices. To examine this hypothesis, we analyze the data produced by different price sets applied to the roads running the UE model with various randomly selected prices that cover the possible ranges of travel demand for each candidate. The prices were chosen using random draws between a minimum (zero) and a maximum (based on a short examination of the minimum price (toll), which decreases own demand dramatically to below about 10%). The sets of prices, then, were produced through repeated randomization of the prices of all links.

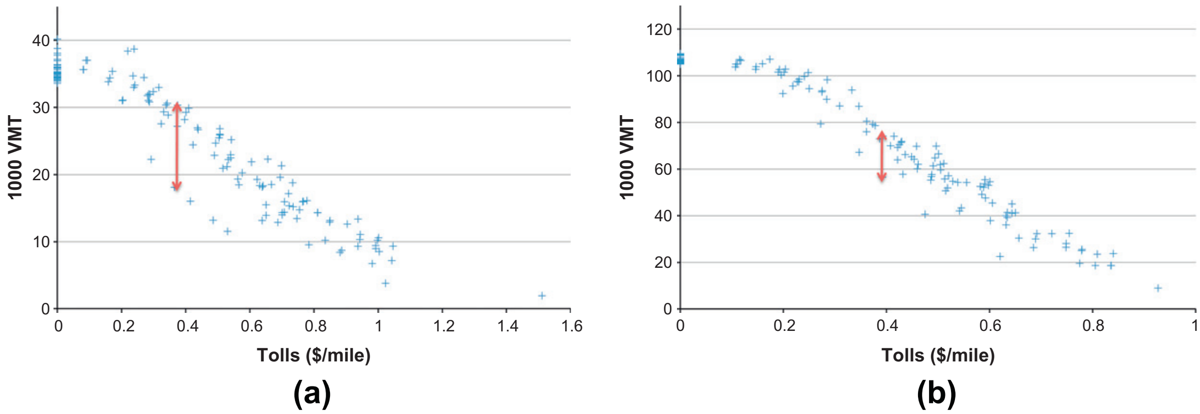

Fig. 2. Hourly vehicle miles traveled (VMT in thousands) for AM peak with respect to own charges for (a) Shaw (an arterial); (b) SR41 (a highway).

Based on the transportation planning model, Fig. 2 shows the total AM peak hourly vehicle miles traveled (VMT) with respect to own prices (charges) on a dollar per mile basis for two candidate roadway segments. For each own price, a wide range of VMTs exists which supports the hypothesis that cross prices might have significant effects on travel demand because own prices are not the only factor affecting travel demand. This is contrary to the finding of Wu et al. (2011), who suggested that the volume per capacity of a private toll road is independent of another competitor's choice of toll. Indeed, their result only applies to a long-run analysis where private entities can increase capacity without any restrictions, which is not the case here.

To further examine our hypothesis, the hourly VMT for all the links (as dependent variables) is regressed against the prices of all links as independent variables, for different functional forms, using Ordinary Least Squares (OLSs). We realize that because of using a system of equation, Seemingly Unrelated Regression (SUR) might be a better fit. But, it is a known fact that when the regressors are the same for all the equations, OLS and SUR results are the same (Greene, 2003, page 344).

The estimated functional forms for each road segment i are as follows:

Linear:

$$q_i = \alpha_{i0} + \alpha_{i1}\tau_1 + \cdots + \alpha_{ij}\tau_j + \cdots + \alpha_{i7}\tau_7 \tag{12}$$

Cobb–Douglas:

$$\ln(q_i) = \alpha_{i0} + \alpha_{i1}\ln(\tau_1) + \cdots + \alpha_{ij}\ln(\tau_j) + \cdots + \alpha_{i7}\ln(\tau_7) \tag{13}$$

Translog (transcendental logarithmic):

$$\begin{aligned}\ln(q_i) = {} & \alpha_{i0} + \alpha_{i1}\ln(\tau_1) + \cdots + \alpha_{ij}\ln(\tau_j) + \cdots + \alpha_{i7}\ln(\tau_7) + \alpha_{ii1}\ln(\tau_i)\cdot\ln(\tau_1) + \cdots + \alpha_{iij}\ln(\tau_i)\cdot\ln(\tau_j) + \cdots + \alpha_{ii7} \\ & \times \ln(\tau_i)\cdot\ln(\tau_7) + \cdots \end{aligned} \tag{14}$$

where q_i is the hourly VMT for road i and τ_j is the toll rate for road j (cents per mile), $i, j = 1,\ldots,7$, and the roads are Shaw, SR168, SR41, SR180, SR99, Shields, and Blackstone, respectively.

We report the coefficients, their standard errors, and adjusted R-squared of the linear and Cobb–Douglas functions for both AM peak and off-peak, and of Translog function for AM peak[3] in Table 2. When comparing the adjusted R-squared, linear functions work well both for AM peak and off-peak. In some cases, the adjusted R-squared of the linear functions are higher than the Translog functions, but the Translog functions include many more explanatory variables. Technically, it is incorrect to compare the R-squares across different functional forms because the total sum of square of the transformed data (logged) is different than the total sum of square for a linear function. However, in our case, the difference between the two R-squared (Linear and Cobb–Douglas) is quite large. The linear relationship can also be observed in Fig. 2. Nevertheless, it is noteworthy that the linearity cannot be used when very high prices are charged (the function asymptotically goes to zero instead of showing the linear relationship).

The coefficients in Table 2 provide some interesting results. A major result is that own-price coefficients (α_{ii}'s) are negative and significant, as expected. Also, the fact that some of the cross coefficients are statistically significant, meaning that the charges applied on one road have a significant effect on the demand of another road, supports the hypothesis that cross prices should have significant effects. That is, the travel demand of a road should be responsive to other roads' prices. How-

[3] Translog function is a common function to estimate demand (Färe et al., 2008; Oum et al., 2000). The advantage of applying a Translog function is that elasticities are not constant and cross price effects can be calculated with this function (Khiabani and Hasani, 2010).

Table 2
Various functional forms (a) linear and Cobb–Douglas for AM peak; (b) linear and Cobb–Douglas for off-peak; and (c) Translog for AM peak.

	α_{i0}	α_{i1}	α_{i2}	α_{i3}	α_{i4}	α_{i5}	α_{i6}	α_{i7}	Adj. R^2
(a)									
Linear									
q_1	34.23	−0.316	0.019	0.034	0.016	0.044	0.012	−0.002	0.949
	(89.79)	(−44.76)	(2.07)	(3.56)	(2.48)	(3.62)	(1.39)	(−0.16)	
q_2	54.28	0.022	−0.629	0.095	−0.062	0.021	−0.003	0.037	0.98
	(140.92)	(3.13)	(−67.14)	(9.96)	(−9.67)	(1.67)	(−0.34)	(3.27)	
q_3	105.56	0.016	0.108	−1.264	0.039	0.101	0.032	0.097	0.983
	(157.21)	(1.27)	(6.59)	(−75.76)	(3.51)	(4.66)	(2.11)	(4.9)	
q_4	56.75	0.014	−0.059	−0.011	−0.473	−0.067	0.017	−0.024	0.941
	(67.65)	(0.91)	(−2.9)	(−0.53)	(−33.71)	(−2.48)	(0.93)	(−0.99)	
q_5	120.14	0.044	0.01	0.109	0.007	−1.761	0.031	0.077	0.978
	(139.38)	(2.78)	(0.46)	(5.1)	(0.51)	(−63.4)	(1.6)	(3.04)	
q_6	14.17	0.019	0.003	0.017	0.027	0.03	−0.148	−0.000	0.935
	(82.24)	(6.1)	(0.72)	(3.92)	(9.39)	(5.36)	(−38.73)	(−0.02)	
q_7	14.35	0.007	0.019	0.109	0.007	0.009	0.002	−0.253	0.892
	(52.16)	(1.36)	(2.91)	(15.91)	(1.44)	(0.96)	(0.37)	(−31.14)	
Cobb Douglas[*]									
$\ln(q_1)$	3.467	−0.406	0.047	0.038	0.059	0.08	0.035	0.038	0.702
	(66.4)	(−16.71)	(1.8)	(1.43)	(2.53)	(2.69)	(1.27)	(1.42)	
$\ln(q_2)$	3.979	0.023	−0.418	0.103	−0.011	0.037	0.028	0.042	0.612
	(59.13)	(0.73)	(−12.38)	(3.03)	(−0.36)	(0.97)	(0.81)	(1.23)	
$\ln(q_3)$	4.645	0.014	0.048	−0.372	0.025	0.080	0.022	0.029	0.597
	(77.39)	(0.52)	(1.58)	(−12.29)	(0.95)	(2.34)	(0.7)	(0.95)	
$\ln(q_4)$	4.148	0.016	−0.021	0.035	−0.439	0.044	0.025	0.019	0.766
	(62.18)	(0.53)	(−0.63)	(1.03)	(−14.77)	(1.17)	(0.71)	(0.55)	
$\ln(q_5)$	4.792	0.029	0.011	0.040	0.017	−0.374	0.035	0.034	0.54
	(72.33)	(0.95)	(0.34)	(1.19)	(0.59)	(−9.95)	(1.02)	(1.01)	
$\ln(q_6)$	2.613	0.032	0.020	0.053	0.80	0.043	−0.346	0.028	0.655
	(55.5)	(1.45)	(0.83)	(2.22)	(3.83)	(1.63)	(−14.03)	(1.14)	
$\ln(q_7)$	2.623	0.053	0.027	0.148	0.036	0.063	0.030	−0.464	0.581
	(38.62)	(1.66)	(0.78)	(4.32)	(1.18)	(1.62)	(0.83)	(−13.32)	
(b)									
Linear									
q_1	15.72	−0.319	−0.004	0.013	0.012	0.007	0.015	−0.001	0.932
	(67.13)	(−37.82)	(−0.41)	(1.72)	(2.32)	(0.97)	(1.73)	(−0.11)	
q_2	27.33	−0.01	−0.487	0.03	−0.046	−0.018	−0.003	0.004	0.982
	(128.61)	(−1.28)	(−61.94)	(4.47)	(−9.67)	(−2.72)	(−0.43)	(0.59)	
q_3	56.73	0.028	0.054	−1.005	−0.008	0.059	0.013	0.013	0.982
	(130.53)	(1.77)	(3.35)	(73.36)	(−0.83)	(4.31)	(0.78)	(0.87)	
q_4	28.62	−0.046	−0.07	−0.063	−0.284	−0.03	0.011	−0.044	0.898
	(48.21)	(−2.15)	(−3.18)	(−3.53)	(−21.63)	(−1.58)	(0.50)	(−2.07)	
q_5	55.17	0.028	−0.008	0.063	−0.01	−1.012	−0.001	−0.023	0.976
	(102.53)	(1.45)	(−0.42)	(3.72)	(−0.87)	(−59.54)	(−0.03)	(−1.18)	
q_6	6.78	0.011	−0.011	0.006	0.012	0.008	−0.141	0.006	0.935
	(68.89)	(2.98)	(−3.02)	(1.93)	(5.55)	(2.48)	(−38.17)	(1.65)	
q_7	5.61	−0.008	0.004	0.06	0.002	0	−0.005	−0.139	0.871
	(37.96)	(−1.48)	(0.77)	(12.93)	(0.62)	(0.01)	(−0.85)	(−26.42)	

(*continued on next page*)

Table 2 (*continued*)

	α_{i0}	α_{i1}	α_{i2}	α_{i3}	α_{i4}	α_{i5}	α_{i6}	α_{i7}	Adj. R^2
Cobb Douglas[*]									
$\ln(q_1)$	5.07	−0.586	0.066	0.087	0.005	0.078	0.041	0.039	0.74
	(80.89)	(−17.18	(1.89)	(2.67)	(0.16)	(2.38)	(1.44)	(1.18)	
$\ln(q_2)$	5.655	0.077	−0.635	0.14	−0.046	0.088	−0.033	0.024	0.692
	(64.94)	(1.63)	(−13.05)	(3.09)	(−1.13)	(1.94)	(−0.82)	(0.54)	
$\ln(q_3)$	6.349	0.031	0.077	−0.623	0.029	0.135	0.038	0.032	0.638
	(70.24)	(0.62)	(1.52)	(−13.21)	(0.7)	(2.86)	(0.91)	(0.68)	
$\ln(q_4)$	5.843	0.022	0.003	0.02	−0.596	0.02	0.006	0.036	0.802
	(72.85)	(0.50)	(0.06)	(0.48)	(−15.96)	(0.48)	(0.16)	(0.87)	
$\ln(q_5)$	6.337	0.05	0.027	0.118	0.027	−0.688	0.029	0.056	0.654
	(60.97)	(0.88)	(0.47)	(2.18)	(0.55)	(−12.73)	(0.61)	(1.03)	
$\ln(q_6)$	4.178	0.083	−0.038	0.025	0.076	0.057	−0.436	0.01	0.731
	(74.5)	(2.72)	(−1.22)	(0.85)	(2.92)	(1.95)	(−17.05)	(0.35)	
$\ln(q_7)$	3.978	0.065	0.026	0.244	0.036	0.035	0.013	−0.673	0.74

	α_{i0}	α_{i1}	α_{i2}	α_{i3}	α_{i4}	α_{i5}	α_{i6}	α_{i7}	α_{ii1}	α_{ii2}	α_{ii3}	α_{ii4}	α_{ii5}	α_{ii6}	α_{ii7}	Adj. R^2
(C)																
Trans Log[*,**]																
$\ln(q_1)$	3.666	0.995	−0.169	−0.161	−0.164	−0.113	−0.207	−0.069	−0.326	0.014	0.059	0.069	0.047	−0.041	0.023	0.969
	(72.78)	(17.83)	(−2.52)	(−2.41)	(−2.90)	(−1.87)	(−2.77)	(−1.19)	(−25.03)	(0.37)	(1.77)	(1.81)	(0.97)	(−0.80)	(0.62)	
$\ln(q_2)$	4.155	−0.169	1.208	−0.189	0.020	−0.146	−0.086	−0.115	0.013	−0.401	0.091	−0.031	−0.063	0.053	0.109	0.969
	(72.79)	(−2.67)	(16.13)	(−2.49)	(0.31)	(−2.13)	(−1.01)	(−1.75)	(0.30)	(−20.76)	(2.23)	(−0.90)	(−1.68)	(1.10)	(2.46)	
$\ln(q_3)$	4.812	−0.115	−0.173	1.300	−0.099	−0.130	−0.136	−0.158	−0.002	−0.029	−0.418	0.075	0.183	−0.061	0.058	0.949
	(75.53)	(−1.63)	(−2.08)	(15.38)	(−1.38)	(−1.70)	(−1.44)	(−2.16)	(−0.06)	(−0.63)	(−18.96)	(1.75)	(3.19)	(−1.30)	(1.34)	
$\ln(q_4)$	4.078	−0.046	0.015	−0.063	0.726	−0.084	−0.052	0.035	0.04	−0.122	0.058	−0.251	0.061	0.021	−0.019	0.992
	(111.51)	(−1.14)	(0.32)	(−1.29)	(17.64)	(−1.92)	(−0.96)	(0.83)	(1.45)	(−5.55)	(2.36)	(−24.68)	(2.71)	(0.83)	(−0.61)	
$\ln(q_5)$	4.817	0.000	0.002	−0.089	−0.106	1.236	−0.156	−0.062	0.088	−0.103	0.064	−0.005	−0.419	0.029	0.084	0.912
	(55.55)	(0.00)	(0.02)	(−0.77)	(−1.09)	(11.88)	(−1.21)	(−0.62)	(1.06)	(−1.82)	(0.81)	(−0.09)	(−14.16)	(0.40)	(1.27)	
$\ln(q_6)$	2.925	−0.250	−0.107	−0.189	−0.190	−0.158	0.864	−0.249	0.122	−0.004	0.027	0.038	0.007	−0.313	0.008	0.933
	(47.05)	(−3.63)	(−1.31)	(−2.29)	(−2.71)	(−2.11)	(9.38)	(−3.48)	(1.92)	(−0.07)	(0.59)	(0.91)	(0.13)	(−12.82)	(0.14)	
$\ln(q_7)$	2.915	−0.094	−0.223	−0.557	−0.190	−0.147	−0.256	0.781	0.125	0.018	0.163	−0.016	0.031	−0.127	−0.341	0.942
	(38.68)	(−1.12)	(−2.26)	(−5.57)	(−2.24)	(−1.63)	(−2.29)	(8.99)	(2.26)	(0.31)	(3.22)	(−0.25)	(0.53)	(−1.88)	(−15.02)	

[*] To solve the problem of zero toll rates for the log functions when using the Cobb Douglas and TransLog functions, 1 cent was added to all the toll rates.
[**] Not all the TransLog functions' coefficients are reported in the table.

ever, in some cases, as shown in Table 2, travel demand for a given road is not always significantly affected by cross prices (e.g., q_1 and τ_7, α_{17} is not significant in linear, Cobb Douglas, and Translog functions).

Another interesting result is that for most roads, the own-price elasticities for AM peak are higher (in absolute values, since elasticities are usually defined in absolute values) than those of off-peak, which likely related to the fact that higher prices are charged for AM peak. It is well-known that peak elasticities should be lower than off-peak because for peak hours, users have less choice and mandatory travel for work. Since the charges are higher for AM peak, their elasticities are also higher due to increasing elasticities in own prices. The own-price elasticities for linear functions are $\frac{\alpha_{ii}\tau_i}{q_i}$ (α_{ii}'s are negative), and for Translog functions are $\alpha_{ii} + \alpha_{iii} \cdot \ln(\tau_i)$ (α_{iii}'s are negative). So the own-price elasticities for both the Translog and linear functions increase in absolute value (decrease in real value) when own prices increase because the second derivatives (α_{iii} for Translog) are negative. As a result, when higher tolls are charged, higher elasticities are expected for peak periods, as shown in Table 2.

A major finding is that cross price effects can change depending on the level of demand. For instance, the α_{25} in the linear functions has positive sign for AM peak (Table 2a) and negative sign for off-peak hours (Table 2b), i.e. Road No. 5 (SR99) is a substitute for Road No. 2 (SR168) on AM peak hours, and is a complement for SR168 on off-peak hours. This suggests that roads can be complements to each other at some levels of demand and become substitutes for each other at other levels. This finding can be crucial not only for a concession model but also for any kind of pricing scheme.

One of the main drivers of the cross prices effects is distance. The closer in proximity the roads are, the more significant the cross prices' coefficients. This is due to the effects of cross charges (prices) on travel demand entering or exiting a prime road, which are higher for roads in closer proximity. However, this is not true for some roads that are far from each other and their effects on each other are still significant. For example, the coefficient of SR180's toll (α_{14}) is significant in both Shaw's demand equations (Table 2a and b, linear equations-q_1) although these road segments are relatively far from each other. On the other hand, the effect of Blackstone's charges on SR41's demand (α_{37}) is not significant for off-peak hours (Table 2b, linear equation-q_3) even though these roads are right next to each other. In addition, the cross price effects are not symmetric (looking at the table, for the linear functions, $\alpha_{ji} \neq \alpha_{ij}$, it can be seen that the cross price coefficients are not the same.

Looking at the Translog function coefficients (Table 2c), all the α_{iii} s (the coefficient of $\ln(\tau_i)^2$ in Eq. (14)) are negative and significant. For Translog functions, the own-price elasticities equal $\frac{d\ln(q_i)}{d\ln(\tau_i)} = \alpha_{ii} + \alpha_{iii} \cdot \ln(\tau_i) \cdot \alpha_{iii}$ is negative and for most of the toll values (usually higher than 5–10 cents), the own-price elasticities decrease when the prices increase (the second derivatives are $\frac{d^2\ln(q_i)}{d\ln(\tau_i)^2} = \alpha_{iii}$). This supports the hypothesis that a linear demand function can be a specification for the data because of the decreasing own-price elasticities characteristic of linear functions.[4]

However, this result might not hold true for higher charges. Our data did not include the right tail of the demand functions. Hence, the adjusted R-squared of the linear demand functions is even higher than those of the Translog functions, which could be reversed if we had more data on the tails of the demand functions. Nevertheless, the simplicity offered by the linear functions makes its use reasonable for our analysis.

4.2. Profit maximization

Realizing the demand functions, we can solve the profit maximization problems. When using different privatization structures, the first order conditions and the resulting prices will change. So, transferring the ownership to one owner (monopoly) should result in different prices than from the prices of oligopoly. The demand functions used for the analysis are the linear functions with all the coefficients, even the statistically non-significant ones.

Table 3 reports the results of solving the first order systems of equations for various ownership structures, which consist of single ownership of each of roads, ownership of all highways, ownership of all roads (monopoly and oligopoly), and two cases of socially optimal pricing. The oligopoly cases represent markets in which each road is owned by a separate firm/owner, and no firm owns more than one road. We should add that our model is unable to capture cross price elasticities between off-peak and peak periods due to the limitations of Fresno's transportation planning model. Future studies may address this limitation.

The total change in welfare in Table 3 is the sum of two measures: first, the change in total travel time (in dollars) and second, the decrease in welfare due to the decrease in travel demand, resulting from any charge, which is calculated hourly and based on the rule of half (Victoria Transport Policy Institute, 2012).

The first observation that arises from this analysis is that in most privatization cases (cases 1 through 10), total travel time is worse (higher) than those of the base case (case 0), i.e., average users are worse off compared to the base case. Thus, privatization should be accompanied with a limit(s) for tolls (toll ceilings). However, privatization of Highway#4 (SR99) is welfare enhancing even without regulations (for both AM peak and off-peak hours), so it is possible to successfully privatize a highway without any price limitations. We will revisit this topic in the social welfare analysis section. Another finding is that in most cases, the AM peak prices are higher than off-peak prices. But, the prices of highways are not necessarily higher than

[4] For linear functions, elasticities are: $d\ln q_i/d\ln \tau_i = \alpha_i \cdot \tau_i/q_i$, so linear functions and Translog functions are similar in that for both, elasticities decrease as prices increase (second derivatives are negative). Translog functions' elasticties are not restricted in this regard. Nevertheless, their elasticities were found to decrease with increasing prices (in our cases). Linear functions restrict the elasticities to be decreasing in prices, and based on the Translog function characteristic, this restriction does not pose a problem. However, the elasticity functions are different in forms.

Table 3
Results of various tolling regimes for (a) AM peak (b) off-peak.

	Scenario	Optimal (Equ.) Prices (cents/mile)							Total hourly profits (1000 $)	Travel time		Total VMT	Reduced demand		Total hourly welfare change (1000 $)
		SR168	SR41	SR180	SR99	Shaw	Shields	Blackstone		Total travel time (Veh-hr)	Hourly welfare change (1000 $)		No. trips	Hourly welfare change (1000 $)	
(a)															
Case 0	Basecase	–	–	–	–	–	–	–	–	103,579	–	3,561,877	–	–	–
Case 1	HW1	33	–	–	–	–	–	–	10.7	104,566	−19.8	3,575,961	118	−0.10	−19.8
Case 2	HW2	–	35	–	–	–	–	–	23.3	105,066	−29.8	3,586,574	177	−0.16	−29.9
Case 3	HW3	–	–	60	–	–	–	–	10.9	104,687	−22.2	3,567,505	181	−0.27	−22.4
Case 4	HW4	–	–	–	26	–	–	–	23.7	103,301	5.6	3,580,953	157	−0.10	5.5
Case 5	Arterial1	–	–	–	–	41	–	–	6.7	103,960	−7.6	3,571,988	93	−0.10	−7.7
Case 6	Arterial2	–	–	–	–	–	43	–	2.6	104,129	−11.0	3,565,636	40	−0.04	−11.1
Case 7	Arterial3	–	–	–	–	–	–	28	1.7	103,670	−1.8	3,565,690	32	−0.02	−1.8
Case 8	All HWs (Olig)	44	46	54	36	–	–	–	75.4	110,501	−138.4	3,638,846	760	−0.86	−139.3
Case 9	Monopoly	54	60	57	42	77	87	64	107.7	111,930	−167.0	3,678,224	1293	−2.04	−169.1
Case 10	Oligopoly	47	49	54	38	64	64	43	104.6	109,800	−124.4	3,667,686	1057	−1.36	−125.8
Case 11	Social Optimal pricing	28	22	16	18	30	32	6	72	100,078	70.0	3,580,068	394	−0.21	69.8
Case 12	Social Optimal pricing-2	27	22	14	18	–	–	–	56	100,420	63.2	3,571,621	316	−0.16	63.0
(b)															
Case 0	Basecase	–	–	–	–	–	–	–	–	36,046	–	1,477,408	–	–	–
Case 1	HW1	24	–	–	–	–	–	–	2.7	36,075	−0.6	1,474,951	53	−0.03	−0.6
Case 2	HW2	–	24	–	–	–	–	–	7.4	35,785	5.2	1,469,909	70	−0.04	5.2
Case 3	HW3	–	–	30	–	–	–	–	3.3	36,128	−1.6	1,474,310	56	−0.04	−1.7
Case 4	HW4	–	–	–	24	–	–	–	7.5	35,740	6.1	1,474,704	81	−0.05	6.1
Case 5	Arterial1	–	–	–	–	18	–	–	1.3	35,880	3.3	1,475,559	23	−0.01	3.3
Case 6	Arterial2	–	–	–	–	–	16	–	0.5	35,686	7.2	1,475,815	9	0.00	7.2
Case 7	Artyerial3	–	–	–	–	–	–	28	0.3	36,085	−0.8	1,477,666	13	−0.01	−0.8
Case 8	All HWs (Olig)	26	29	43	28	–	–	–	20.5	36,144	−2.0	1,464,951	297	−0.23	−2.2
Case 9	Monopoly	25	31	38	28	26	27	20	25.9	36,281	−4.7	1,467,043	354	−0.25	−4.9
Case 10	Oligopoly	26	30	39	28	27	28	26	25.4	36,374	−6.7	1,501,248	361	−0.26	−7.0
Case 11	Social optimal pricing*	11	14	11	13	13	14	3	19.1	35,144	18.0	1,463,900	149	−0.04	18.0
Case 12	Social optimal pricing-2*	11	14	9	11	–	–	–	16.2	35,182	17.3	1,465,366	114	−0.03	17.3

∗ To find socially optimal prices, we use a simple local search algorithm considering Tabu search ideas. For more information about Tabu Search, see Poorzahedy and Rouhani (2007).

the prices of arterials. These results confirm that flexible but limited tolls are important; toll limits should be different for different periods of time. Also, AM peak private cases are more prone to reducing welfare than are off-peak cases, and in instances where welfare is reduced, the negative effects are greater for the AM cases than for off-peak cases. This provides an important policy insight regarding scheduling toll limits.

As an interesting example, for the monopoly case (case 9) and AM peak (Table 3a), the prices charged for the arterials are significantly higher than those of highways. This can be related to the fact that the private owner attempts to direct the flows from arterials to highways, which worsens the flow pattern in terms of total travel time. As an extreme result of pricing, for the monopoly case – AM peak (case 9, Table 3a), total travel time is about 7% higher than the total travel time of base case. Also, the total profits gathered from the oligopoly and monopoly cases for both periods are very close even though the prices charged for some roads in the monopoly cases are much higher than the oligopoly prices. Theoretically, this possibly points to private road owners' expectation of an aggressive response from other owners to their price change, which results in a solution close to a monopoly (Díaz et al., 2010). The aggressive response could be a concern in practice, but it is outside the scope of the model.

Table 3 also reports the socially optimal pricing for two cases, case 11 (when only highways are priced) and case 12 (when all road segments are priced). The socially optimal prices are calculated based on minimizing total travel time (the total VMT or the combination of these can be also used). The socially optimal prices are much lower than the prices charged for the privately owned cases, sometimes approaching less than one-third.

While unlimited private charges can increase the total travel time, socially optimal prices can decrease the total travel time by about 3%. Using social cost pricing, charging arterial road users, in addition to highway users, can help to decrease total travel time, and for the AM peak cases the difference is significant (about 0.5% decrease going from case 12 to case 11). Although 0.5% change in the total travel time might seem trivial, for a large-size city, this change might lead to millions of dollars of time saving. This shows that in addition to highway/freeways, we should reconsider privatizing/pricing arterials.

The significant difference between socially optimal prices for peak and off-peak periods (Table 3a vs. 3b) suggests that flexible but limited price schedules should be involved in leasing agreements. For all the cases studied, limiting the prices (price ceilings) guarantees that prices will be set at socially optimal levels. In fact, the calculated solution of the constrained optimization problems, using new constrained first order conditions and the Bertrand–Nash equilibrium concept, is at the price limits (which are set at socially optimal levels). This is true for all profit maximization cases. However, in general, some private owners may undercut the socially optimal prices, which are set as the maximum prices to be charged, to increase their profits which in turn, requires a lower limit(s) for the prices as well as an upper limit(s). If there is a possibility of undercutting, the policy maker(s) should set rigid prices (both lower and upper limits).

4.3. Social welfare analysis

The main goal of the policy makers is to improve the transportation system performance. Different measures are typically considered. One important, but not comprehensive and rather isolated, measure is the usage of the resources, i.e., volume per capacity for roads. Fig. 3 shows the volume per capacity for different ownership structures on two candidate roadway segments. For both unlimited private ownership structures, monopoly and oligopoly cases, the volumes per capacity are set at very low levels, implying the underusage of resources; especially, the monopoly cases' volume per capacities are the lowest (Mon. cases in both figures). Also, highway-only socially optimal pricing (S.O.2 case) can increase volume per capacity beyond the base case (Fig. 3a), implying overusage of resources (arterials). This suggests that even for socially optimal pricing, some arterials should be priced to improve the usage of roads.

Table 4 presents a number of typical system-level measures for different tolling regimes. The figures reported in the table are the combination of off-peak (18 h) and peak (6 h). For simplicity, we only considered the AM peak results. Another reason for the replacement is that PM peak volumes are noisier than those of AM peak. Modeling the PM peak is more challenging because of the lower estimation power. The annual total change in welfare is the sum of the change in travel time and the decrease in welfare from the demand decrease. Other variables such as environmental effects, gasoline consumption, and total VMT could be added to the welfare measure. Nevertheless, most of these measures are correlated to total travel time. In fact, adding these measures to the calculation will increase the absolute values of the welfare measure, possibly non-linearly.

The first and perhaps the most important result is that unconstrained pricing can decrease social welfare relative to the base case. In that case, a high percentage of the decrease results from higher total travel time, due to inefficient pricing for the whole system (even though it might be efficient for the private roads). The decrease in social welfare can be enormous for a city like Fresno.

While unlimited pricing can worsen the situation, using socially optimal charges or limiting the prices can drastically improve system performance. Instead of a loss of around $300 million per year, the transportation system could increase welfare by about $200 million annually.[5] Most of the welfare effect is from the changes in total travel time rather than suppressing trips. This result is due to more efficient rerouting. However, the result might be a product of our model specification (i.e., the model might underestimate the welfare loss due to decrease in trips).

[5] The revenue from pricing, at least partially considering private entity profits, can be redistributed to users either in the form of direct payments or improvement of the transportation system. So, the charges are not social welfare costs but rather transfers from one group of people to another.

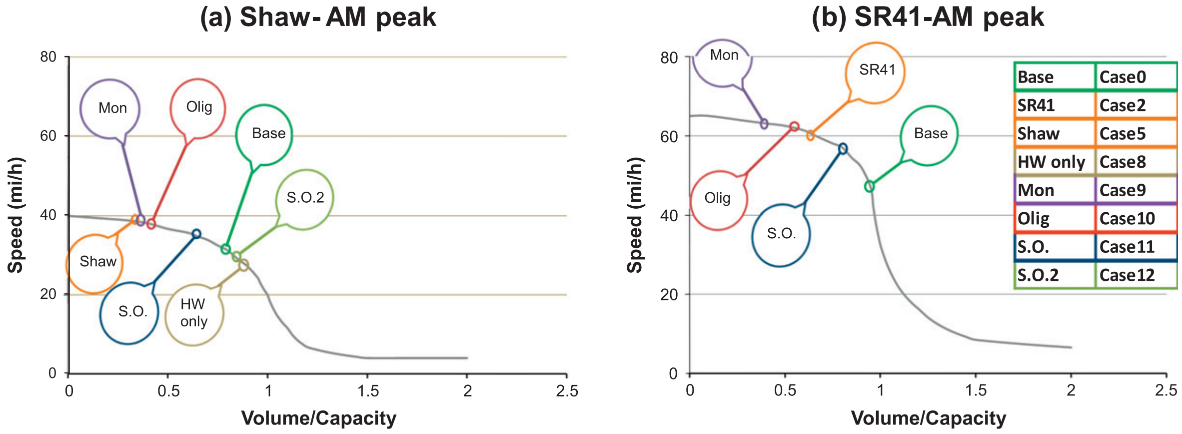

Fig. 3. Speed vs. volume per capacity considering different cases for (a) Shaw (an arterial); (b) SR41 (a highway).

Table 4
Results of various tolling regimes, considering combination of peak and off-peak hours.

	Scenario	Total annual profits (million $)	Change in total travel time (Ave. Veh-hr)		Change in travel demand (# trips)		Total change in welfare (million $)
			Percent change	Annual Welfare change (million $)	Percent change	Annual Welfare change (million $)	
Case 0	Basecase	–	–	–	–	–	–
Case 1	HW1	28.2	0.51	−32.2	−0.04	−0.3	−32.5
Case 2	HW2	68.1	0.33	−21.3	−0.06	−0.4	−21.7
Case 5	Arterial1	16.0	−0.06	3.5	−0.02	−0.2	3.3
Case 8	All HWs (Olig)	205.5	3.41	−216.3	−0.24	−2.2	−218.5
Case 9	Monopoly (all)	278.3	4.28	−280.9	−0.34	−3.9	−284.8
Case 10	Oligopoly (all)	273.7	3.40	−225.4	−0.31	−3.1	−228.5
Case 11	Socially optimal pricing	194.0	−2.93	195.0	−0.12	−0.5	194.4
Case 12	Socially optimal pricing-2	156.8	−2.72	167.5	−0.10	−0.2	167.3

One interesting implication from this analysis is that the total annual profits for the socially optimal pricing cases are relatively close to the profits collected under unlimited pricing schemes (monopoly and oligopoly cases). Although private owners could increase their profits by charging higher prices, leasing the roads can still be a profitable investment for private owners when the prices are capped. Privatizing/pricing the arterials not only can improve system performance, but may also increase the profits from the pricing both overall and for each highway owner. This emphasizes that policy makers/officials should consider privatizing arterials.

5. Conclusions

Modeling is always associated with limitations and simplifications. Considering such limitations and simplifications is essential to interpreting results and to providing reliable policy insights. In our analysis, three key limitations stand out. First, while multi-class user equilibrium is a requirement for analyzing policies related to pricing, the available city-size models usually do not cover multiple users. An alternative approach to the single user equilibrium used in this study is to implement simplified assumptions based on Rouhani and Niemeier (2011) to capture the multi-user characteristic to some extent. But to properly justify use of a multi-user model, one needs to know the distribution of value of time for user of each origin/destination pair. The second major limitation of our analysis is that the city of Fresno does not have a strong public transportation system. Our earlier study (Rouhani and Niemeier, 2011) suggests that one of the main advantages of privatization lies in increasing the share of public transportation, which is crucial for improving system performance. Because Fresno has no significant public transportation, our analysis may underestimate the benefits of privatization. Finally, our model simulates a static process, so it fails to capture some of the potential benefits of privatization such as incremental profits which can be used for financing more projects and increasing capacity in the long-run.

Despite these limitations, the model provides new and very useful policy insights. First, each link's travel demand is a function of other links' prices. Thus, roads cannot be considered as isolated elements in a concession model for a road network. The own-price elasticities are not constant and decrease (increase in absolute values) with increasing prices. Roads can function as complements at some levels of demand and become substitutes at other levels. The profit maximizing problem suggests additional useful policy implications. It is clear that in some circumstances, privatizing/pricing arterials can improve system performance; our analysis also identifies that, in addition, the total profits from the pricing as well as those for each highway owner may increase (sometimes substantially). Hence, some thought should be given for the privatizing/pricing of arterials.

Profits under socially optimal pricing are relatively close to the profits under unlimited pricing. Thus, leasing the roads can still be a profitable investment even when using regulations like price ceilings. In addition, unconstrained pricing can decrease social welfare and should not be implemented when social welfare is sought. Therefore, a limited pricing schedule can be profitable with social welfare improvement as an ancillary benefit, while unlimited pricing can lead to inefficient use of transportation systems.

Given the limitations of this study, future studies may consider applying this model to an urban transportation network with a strong public transit system to study the impacts on alternative modes to personal vehicles. The addition of a public transit system can bring new insights into the effects of privatization. Although travel demand is assumed to be flexible in the study, the endogenous travel demand elasticities are not calibrated for the significant changes in travel costs as a result of charging. Further research is required to improve the elasticities in this regard.

6. Caveat

The transportation planning model used in this study is only for research purposes, and not for developing regional transportation plans or transportation improvement programs.

Acknowledgements

The authors express their special gratitude to Alissa Kendall, Michael Zhang, Richard Sexton, and James Chalfant at the University of California, Davis for their insightful comments, and Song Bai at Sonoma Technology, Inc. for providing the analysis data. In addition, the authors would like to thank the reviewer for his valuable comments.

References

AASHTO Website, 2012. Availability Payments Definition, <http://www.transportation-finance.org/funding_financing/financing/other_finance_mechanisms/availability_payments.aspx> (accessed May 2012).
Arup/Parsons Brinckerhoff (PB) Joint Venture, 2010. Analysis of Delivery Options for the Presidio Parkway Project, California Transportation Center (CTC) Project Proposal Report.
Bel, G., Foote, J., 2009. Tolls, terms, and public interest in road concessions privatization: a comparative analysis of recent transactions in the US and France. Transport Reviews 29 (3), 397–413.
Bierman, H.S., Fernandez, L., 1998. Game Theory: With Economic Application. Addison-Wesley Publishing Company, Inc., Reading, MA.
Bonnafous, A., 2010. Programming, optimal pricing and partnership contract for infrastructures in PPPs. Research in Transportation Economics 30 (1), 15–22.
Chen, A., Subprasom, K., 2007. Analysis of regulation and policy of private toll roads in a Build-Operate-Transfer scheme under demand uncertainty. Transportation Research Part A 41 (6), 537–558.
Chung, D., Hensher, D.A., Rose, J.M., 2010. Toward the betterment of risk allocation: investigating risk perceptions of Australian stakeholder groups to public–private-partnership toll road projects. Research in Transportation Economics 30 (1), 43–58.
City of Fresno Website, 2012. <http://www.fresno.gov/DiscoverFresno/default.htm> (accessed June 2012).
Crowe Chizek and Company LLC, 2006. State of Indiana East–West Toll Road Financial Analysis. Submitted Report to the State of Indiana, Indiana Finance Authority by: Crowe Chizek and Company LLC, Indianapolis, Indiana.
de Jong, M., Mu, R., Stead, D., Ma, Y., Xi, B., 2010. Introducing public–private partnerships for metropolitan subways in China: what is the evidence? Journal of Transport Geography 18 (2), 301–313.
de Palma, A., Lindsey, R., 2000. Private toll roads: competition under various ownership regimes. Annals of Regional Science 34 (1), 13–35.
de Palma, A., Lindsey, R., 2002. Private roads, competition and incentives to adopt time-based congestion tolling. Journal of Urban Economics 52 (2), 217–241.
de Palma, A., Kilani, M., Lindsey, R., 2007. Maintenance, service quality and congestion pricing with competing roads. Transportation Research Part B 41 (5), 573–591.
Díaz, C.A., Villar, J., Campos, F.A., Reneses, J., 2010. Electricity markets equilibrium based on conjectural variations. Electric Power Systems Research 80 (12), 384–392.
Dimitriou, L., Tsekeris, T., Stathopoulos, A., 2009. Joint pricing and design of urban highways with spatial and user group heterogeneity. Netnomics 10 (1), 141–160.
Engel, E., Fischer, R., Galetovic, A., 2003. Privatizing highways in Latin America: fixing what went wrong. Economia 4 (1), 129–158.
Engel, E., Fischer, R., Galetovic, A., 2006. Privatizing highways in the United States. Review of Industrial Organization 29 (1), 27–53.
Evenhuis, E., Vickerman, R., 2010. Transport pricing and public–private partnerships in theory: issues and suggestions. Research in Transportation Economics 30 (1), 6–14.
Färe, R., Grosskopf, S., Hayes, K.J., Margaritis, D., 2008. Estimating demand with distance functions: parameterization in the primal and dual. Journal of Econometrics 147 (2), 266–274.
Greene, W., 2003. Econometric Analysis, Fifth ed. Prentice Hall, Page, 344.
Indiana Toll Road Website, 2012. <https://www.getizoom.com/index.jsp> (accessed July 2012).
Jacquemin, A., 1987. The New Industrial Organization: Market Forces and Strategic Behavior. Clarendon Press, Oxford, UK.
Khiabani, N., Hasani, K., 2010. Technical and allocative inefficiencies and factor elasticities of substitution: an analysis of energy waste in Iran's manufacturing. Energy Economics 32 (5), 1182–1190.
Madani, K., 2011. Hydropower licensing and climate change: insights from game theory. Advances in Water Resources 34 (2), 174–183.
Madani, K., Dinar, A., 2012. Non-cooperative institutions for sustainable common pool resource management: application to groundwater. Ecological Economics 74 (2012), 34–45.
Magnan de Bornier, J., 1992. The 'Cournot–Bertrand Debate': a historical perspective. History of Political Economy 24 (3), 623–654.
Mallozzi, L., 2007. Noncooperative facility location games. Operations Research Letters 35 (2), 151–154.

Nagurney, A., 2000. Sustainable Transportation Network. Edward Elgar Publishing Inc., Northampton, Massachusetts, USA.
NAO (National Audit Office), 1998. The Private Finance Initiative: The First Four Design, Build, Finance and Operate Roads Contracts. Report by the Comptroller and Auditor General, HC 476, Session 1997e1998. The Stationery Office, London.
Ortiz, I.N., Buxbaum, J.N., Little, R., 2008. Protecting the public interest – role of long-term concession agreements for providing transportation infrastructure. Transportation Research Record 2079, 88–95.
Oum, T.H., Zhang, A., Zhang, Y., 2000. Socially optimal capacity and capital structure in Oligopoly: the case of the airline industry. Journal of Transport Economics and Policy 34 (1), 55–68.
Poorzahedy, H., Rouhani, O.M., 2007. Hybrid meta-heuristic algorithms for solving transportation network design. European Journal of Operational Research 182 (2), 578–596.
Rall, J., Reed, J.B., Farber, N.J., 2010. Public–private partnerships for transportation, a toolkit for legislators. In: The National Conference of State Legislatures, The Forum for America's Ideas. ISBN 978-1-58024-612-5.
Reason Foundation, 2009. Annual Privatization Report, edited by L.C. Gilroy.
Reinhardt, W., 2011. The Role of Private Investment in Meeting U.S. Transportation Infrastructure Needs. American Road & Transportation Builders Association (ARTBA) Transportation Development Foundation (May 2011).
Rouhani, O.M., 2009. Road privatization and sustainability. MIT Journal of Planning 6, 82–105.
Rouhani, O.M., Niemeier, D., 2011. Urban network privatization: a small network example. Transportation Research Record 2221, 46–56.
Sheffi, Y., 1984. Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods. Prentice-Hall, Englewood Cliffs, NJ.
Verhoef, E.T., Nijkamp, P., Rietveld, P., 1996. Second-best congestion pricing: the case of an un-tolled alternative. Journal of Urban Economics 40 (3), 279–302.
Victoria Transport Policy Institute, 2012. Transportation Cost and Benefit Analysis II, Evaluating Transportation Benefits. 3–7. <www.vtpi.org/tca/tca07.pdf> (accessed July 2012).
Wang, J.Y.T., Lindsey, R., Yang, H., 2011. Nonlinear pricing on private roads with congestion and toll collection costs. Transportation Research Part B 45 (1), 9–40.
Wardrop, J.G., 1952. Some theoretical aspects of road traffic research. Proceedings of the Institute of Civil Engineers, Part II, 325–378.
Waterson, M., 1984. Economic Theory of the Industry. Cambridge University Press, Cambridge, MA.
Watson, J., 2002. Strategy: An Introduction to Game Theory, 1st ed. W.W. Norton & Company, Inc., New York.
Winkelman, S., Bishins, A., Kooshian, C., 2010. Planning for economic and environmental resilience. Transportation Research Part A 44 (8), 575–586.
Winston, C., Yan, J., 2011. Can privatization of U.S. highways improve motorists' welfare? Journal of Public Economics 95 (7–8), 993–1005.
Wu, D., Yin, Y., Yang, H., 2011. The independence of volume-capacity ratio of private toll roads in general networks. Transportation Research Part B 45 (1), 96–101.
Yang, H., Tang, W.H., Cheung, W.M., Meng, Q., 2002. Profitability and welfare gain of private toll roads in a network with heterogeneous users. Transportation Research Part A 36 (6), 537–554.
Yin, Y., 2000. Genetic algorithm-based approach for bilevel programming models. Journal of Transportation Engineering: ASCE 26 (2), 115–120.
Zhang, X.Q., 2005. Critical success factors for public–private partnerships in infrastructure development. Journal of Construction Engineering and Management 131 (1), 3–14.
Zhang, L., 2008. Welfare and financial implications of unleashing private-sector investment resources on transportation networks. Transportation Research Record 2079, 96–108.
Zhang, L., Levinson, D., 2006. Road pricing with autonomous links. Transportation Research Record 1932, 147–155.
Zhang, L., Levinson, D., 2009. The economics of road network ownership: an agent-based approach. International Journal of Sustainable Transportation 3 (5–6), 339–359.